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Paleo-Tethyan Evolution of Tibet as Recorded in the East Cimmerides and West Cathaysides

Zhiqin Xu^{a,*}, Yildirim Dilek^{a, c}, Hui Cao^a, Jingsui Yang^a, Paul Robinson^d, Changqian Ma^e, Huaqi Li^a, Marc Jolivet^f, Françoise Roger^g, Xijie Chen^a

^aState Key Laboratory of Continental Tectonics and Dynamics, Institute of Geology, Chinese Academy of Geological Sciences, Beijing 100037, China

^bState Key Laboratory for Mineral Deposits Research, Department of Earth Sciences, Nanjing University, Nanjing 210093, China

^cDepartment of Geology & Environmental Earth Science, Miami University, Oxford, OH 45056, USA

^dDepartment of Earth Sciences, Dalhousie University, Halifax, Nova Scotia, Canada B3H4J1

^eChina University of Geosciences, Wuhan 430074, China

^fUMR 6118 - CNRS - University Rennes 1, Campus de Beaulieu, 35042 RENNES Cédex, France

^gUniversité Montpellier 2, Place Eugène Bataillon, 34095 Montpellier Cedex 05, France

Corresponding Author:

Dr. Zhiqin Xu

Tel.: +86-01068999663

Email: xuzhiqin@gmail.com

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Abstract

The Paleozoic-early Mesozoic geology of Tibet was controlled by the rift-drift, seafloor spreading and subduction zone tectonics of a Paleo-Tethyan realm, which evolved between the West Cathaysides (WC) and the East Cimmerides (EC). Different suture zones with ophiolites and ophiolitic mélanges, high-pressure metamorphic belts, magmatic arcs and accretionary prism complexes separating different terranes mark multiple subduction-accretion systems within this Paleo-Tethyan domain, reminiscent of the modern Western Pacific Ocean. Discrete basins separated by different continental blocks and magmatic arcs constituted a complex paleogeography of Paleo-Tethys, and these oceanic strands were closed as a result of subduction with different polarities during the late Paleozoic-Triassic. The Longmu Tso Shuanghu-Changning Menglian Suture zone (LS-CMS) in Tibet represents the main tectonic boundary between the WC and EC that developed in the Devonian. The East Kunlun-A'nyemaqen oceanic slab was subducted northward beneath the East Kunlun terrane in northern Tibet, whereas the Sumdo oceanic slab was subducted northward beneath the South Qiangtang-North Lhasa terrane in southern Tibet. The Longmu Tso Shuanghu-Changning Menglian and Jinshajiang-Ailaoshan-Song Ma ophiolites were developed and emplaced in subduction-accretion systems with opposite polarities (westward and eastward) beneath the North Qiangtang-Qamdo-Simao-Indochina terrane in central Tibet. The Jinshajiang-Ailaoshan-Song Ma oceanic slab was subducted westward beneath the North Qiangtang-Simao-Indochina terrane along the Jinshajiang and Ailaoshan-Song Ma trenches in a trench-ridge-trench triple junction plate configuration. The Emeishan mantle plume produced a large Permian basaltic terrane, developed on the western passive margin of the South China block. The final closure of the Paleo-Tethyan oceanic branches resulted in continental collisions and development of a vast Indosinian orogenic collage in the latest Triassic-Jurassic.

Key words: Paleo-Tethyan Tibet; Orogenic collage; Cimmerides; Cathaysides; Paleo-Tethys; Ophiolites and suture zones; Décollement-type orogen

1. Introduction

Reconstructions of Pangea and Tethys for the time interval of 295-200 Ma (**Fig. 1**; Dilek and Rowland, 1993; Dilek et al., 1999; Dilek and Robinson, 2003; Flower and Dilek, 2003; Scotese, 2004; Metcalfe, 2011, 2013) indicates that the Paleo-Tethyan and Neo-Tethyan oceanic realms developed in the wake of northward-drifting ribbon continents and continental masses that were rifted off from the northern edge of Gondwana (**Fig. 1**; Dilek and Rowland, 1993; Dilek et al., 1999; Dilek and Robinson, 2003; Scotese, 2004; Metcalfe, 2011, 2013). The Cimmerides represent one of these continental masses whose remnants are now found in Anatolia, Persia, Afghanistan and Tibet (Metcalfe, 1996a, b; Metcalfe, 1999; **Fig. 1**). The Cathaysides included mainly the South China, Indochina, Sibumasu and Qamdo continental blocks and were already part of the Paleo-Tethyan realm since the Sedonian (Wegener, 1912; Morel and Irving, 1981; Parrish, 1993; Collins et al., 2003). The evolution of Paleo-Tethys, as recorded in the geology of Tibet, was controlled to the largest extent by the tectonic interactions between the Cathaysides and the Cimmerides during much of the late Paleozoic-early Mesozoic. The Gondwana-derived terranes that are currently separated by a series of suture zones in Tibet migrated across the Paleo-Tethyan Ocean and were accreted into Asian continental margins during the late Paleozoic and Mesozoic. The final closure of the Paleo-Tethyan Ocean resulted in collision of the East Cimmerides and the West Cathaysides in Tibet, and led to the development of a vast orogenic belt (Indosinian orogenic belt) in South Asia (Fromaget, 1927, 1929, 1934, 1952; Huang, 1945; Ren and Qu, 1966).

A new Permian paleogeographic reconstruction of northern Peri-Gondwana and Paleo-Tethys with a focus on Tibet (**Fig. 2**; Metcalfe, 2002) indicates that Permian marine strata occurred in an array of blocks containing diverse faunas of different biogeographical affinities. The North Qiangtang-Qamdo Block contains Permian marine faunas of typically Cathaysian character, whereas the Himalaya Tethys zone in southern Tibet is characterized primarily by cold-water faunas. The South Qiangtang and Lhasa blocks are characterized by mixed warm- and cold-water faunas supplemented with a strong endemic component (Zhang et al., 2013).

In this paper, we present an overview of the tectonic evolution of Paleo-Tethys as recorded in the geological history of the East Cimmerides and West Cathaysides. We examine the structure and geochronology of different continental blocks, island arcs and magmatic arcs, accretionary prism complexes, ophiolites and suture zones that collectively represent the Paleozoic-early Mesozoic geology of the East Cimmerides and West Cathaysides, and the Paleo-Tethyan oceanic strands in between them. This overview and the tectonic model presented in the last part of the paper are based on the extant literature and our own work in Tibet and in the surrounding regions. As we review the existing and new data on the Paleo-Tethyan evolution of Tibet, we focus on the following fundamental questions related to its Paleo-Tethyan tectonics: (1) How does the geology of the East Cimmerides (EC) and West Cathaysides (WC) reflect the Paleo-Tethyan tectonics in Tibet? (2) What were the timings of the opening and the closure of different strands of the Paleo-Tethyan Ocean, and what were the subduction polarities within them as they closed? (3) How did the amalgamation of various continental blocks and arc terranes within the Paleo-Tethyan realm occur, leading to the final closure of Paleo-Tethys and to the development of the Indosinian orogenic collage?

2. Paleo-Tethyan tectonic framework in Tibet

The Paleo-Tethyan realm in Tibet can be subdivided, based on the occurrence of markedly distinct Permian and younger sedimentary sequences and faunal successions in them (Ueno et al., 2003; Zhang et al., 2013), into two main domains: The East Cimmerides to the west and the West Cathaysides to the east (Metcalf, 1999). The East Cimmerides includes the South Qiangtang/North Lhasa (SQT-NLS) - Baoshan (BS) - Sibumasu (SB) terranes to the north and the South Lhasa terrane to the south (**Fig. 3**). The West Cathaysides in Tibet includes the North Qiangtang–Qamdo–Simao–Indochina and Songpan–Ganze terranes (**Fig. 3**). The final collision between the East Cimmerides and West Cathaysides resulted in the build-up of a broad Paleo-Tethyan (or Indosinian) orogenic belt during the latest Triassic and Jurassic (Xu et al., 2013) that is characterized by multiple ribbon terranes, Paleozoic ophiolites, island arc complexes, high pressure metamorphic belts, and fossil accretionary prism complexes.

Major fault systems separating these various tectonic entities in Tibet developed during their juxtaposition as the Paleo-Tethyan oceanic realm diminished. The Longmu Tso Shuanghu-Changning Menglian suture zone, which separates the East Cimmerides from the West Cathaysides (**Fig. 3**), represents the most important suture zone within the Paleo-Tethyan system in Tibet. The E-W trending Kunlun-A'nyemaqen suture zone in the West Cathaysides lies between the Songpan Ganze terrane to south and the Kunlun terrane to north, and the Jinshajiang-Ailaoshan-Song Ma suture zone separates the North Qiantang-Qamdo-Simao-Indochina terrane from the South China Block and the Songpan Ganze terrane (**Fig. 3**). The newly discovered Paleo-Tethyan Sumdo suture zone occurs between the South Qiantang-North Lhasa and South Lhasa terranes of southern Tibet (**Fig. 3**; Yang et al., 2006; Chen et al., 2009). Numerous ophiolites and ophiolitic mélanges, high-pressure metamorphic units, magmatic arcs, and accretionary wedges with abundant exotic blocks are exposed along all these suture zones (Xu et al., 2013).

Accretionary orogens related to oceanic subduction develop at intraoceanic and continental convergent margins and include forearc, arc and backarc components (Dilek, 2006; Cawood et al., 2009a, b). Accretionary orogens are variably deformed and metamorphosed through subduction processes and tectonothermal events, as commonly recorded in sub-parallel, high-T-high-P belts (Miyashiro, 1973; Ernst, 2005; Brown, 2006, 2009). Paleo-Tethyan subduction systems (i.e. magmatic arc terranes and accretionary complexes) in Tibet occur along several well-recognized suture zones. Paleo-Tethyan arc terranes and subduction-accretionary wedges are exposed in central and south-southeastern Tibet, including the Lincang arc terrane on the eastern side of the Changning-Menglian suture zone, the Yidun arc terrane between the Jinshajiang and Litang suture zones, the Bulhanbuda Arc and West Qinling accretionary wedge on the northern side of the East Kunlun-A'nyemaqen suture zone, as well as the Sumdo subduction-accretionary terrane between the South Qiantang-North Lhasa and South Lhasa terranes.

2.1 Paleo-Tethyan terranes in Tibet

2.1.1 West Cathaysides (WC)

The West Cathaysides in Tibet consist of the Songpan-Ganze and the North Qiangtang–Qamdo–Simao–Indochina terranes, which are connected with the Proto-Tethyan Qilianshan–Qadam–East Kunlun terranes to the north and with the South China Block to the east (**Fig. 3**).

Songpan-Ganze (SPGZ) terrane: The Songpan-Ganze terrane is separated from the Paleo-Tethyan Qilian–East Kunlun terrane to the north by the A'nyemaqen suture zone, the North Qiangtang–Qamdo–Simao–Indochina terranes to the southwest by the Jinshajiang suture zone, and the Yangtze block to the east by the Longmen Shan suture zone.

The Triassic Songpan-Ganze orogeny resulted from plate boundary interactions between the Yangtze, North China, and Qiangtang blocks during the closure of the Paleo-Tethyan Ocean. The orogenic belt is composed mainly of, from west to east, the Bayan Har, Songpan-Ganze, Yidun (or Litang–Batang) and Longmenshan terranes. The Songpan-Ganze terrane is divided by the NW-SE-oriented Xiangshuihe fault into two parts: the Danba Unit to the east and Muli Unit to the west that are composed of Precambrian basement rocks and Paleozoic-Triassic cover series (Xu et al., 1992; Roger et al., 2004).

The Songpan-Ganze terrane includes a Middle Upper Triassic flysch unit and pre-Triassic rocks (Xu et al., 1992). The Triassic flysch unit occupies a triangular-shaped area between the East Kunlun terrane to the north, the Longmen Shan to the east and the Yidun arc terrane to the southwest, and consists of more than 10-km-thick clastic rock sequences. It has been considered to represent a giant fan deposit, analogous to the modern Bengal fan in the Indian Ocean. Triassic-Jurassic clastic sedimentary rocks occur to the east of the flysch units, and are highly deformed. They are similar in age and lithology to those clastic rock units in the Yangtze Block.

The Neoproterozoic basement crops out only in the southeastern part, in the Danba, Muli, Xuelongbao and Longmen-Shan areas (Xu et al., 1992; Roger and Calassou, 1997; Zhou et al. 2002, 2006a, b), and consists mainly of a crystalline complex with ages around 748–884 Ma (Roger et al., 2004). The late Proterozoic granitoids represent calc-alkaline intrusions that formed above a south-dipping subduction zone beneath the

Yangtze block during 1000-850 Ma (Gao et al., 1990; Kröner et al., 1993). The nature of the basement below the Triassic sedimentary basin to the north remains unknown.

The Songpan Ganze terrane does not represent a typical collisional orogeny. The large volume of accreted Triassic sedimentary rocks between the North China, Qiangtang and Yangtze did not allow a complete continent-continent collision (Roger et al., 2004). Major tectonic structures in Longmen Shan of the eastern margin of the Tibetan plateau have been reactivated by strike-slip faults during the Tertiary.

The Songpan-Ganze terrane is juxtaposed against the Tianshuihai terrane in the west along the NE-SW-striking, sinistral Altyn Tagh fault. The Tianshuihai terrane is bounded by the West Kunlun terrane to the north and the West Qiangtang terrane to the south, separated by the nearly E-W-extending West Kunlun suture zone and the NW-SE-running Kalakunlun fault, respectively. The pre-Sinian metamorphic basement of the Tianshuihai terrane is exposed in its northwestern part, consisting of medium- to high-grade granulite to amphibolite-facies rocks. In the early Paleozoic, the Tianshuihai region was covered predominantly by continental slope facies and turbiditic clastic deposits, calcareous mudstones of a flysch sequence, and abyssal deposits. Subsequently, all these units were deformed and metamorphosed during an early Paleozoic orogeny, followed by the deposition of Upper Devonian foreland basin sedimentary rocks, consisting of marine and terrestrial molasse deposits (Ding et al., 1996). A thick, Permian-Triassic flysch succession represents a Paleo-Tethyan product. All these units were subsequently deformed during the Indosinian orogeny. Post-orogenic granites were emplaced at 246-190 Ma (Arnaud, 1992; Xu et al., 1992).

North Qiangtang–Qamdo–Simao–Indochina terrane: The North Qiangtang–Qamdo–Simao–Indochina terrane is bounded by the Jinshajiang–Ailaoshan–Song Ma suture zone to the north and the east, and by the Longmu Tso Shuanghu–Changning Menliang suture zone to the south and the west. It is located between the Songpan-Ganze and South Qiangtang–North Lhasa–Baoshan–Subumasu terranes (**Fig. 3**).

The Qiangtang terrane has been divided into northern and southern sub-regions based on the recent discovery and identification of the Longmu Tso-Shuanghu Paleo-Tethyan suture zone. Based on the results of paleontological studies of the fauna and

flora, the Longmu Tso-Shuanghu and Changning-Mengliao suture zones can be combined to represent the boundaries of the West Cathaysides and the East Cimmerides, separating the North Qiangtang–Qamdo–Simao–Indochina terrane and the South Qiangtang–Baoshan–Sibumasu terrane.

The North Qiangtang–Qamdo–Simao–Indochina terrane consists mainly of Upper Paleozoic and Mesozoic sedimentary rocks, overlain by Cenozoic basinal strata. The metamorphic basement of the Amugang Group includes 519-530 Ma gneisses and is distributed mainly in the southern margin of the terrane (Chang et al., 1986; Xu et al., 1997). In the Ordovician-Permian, the Qiangtang terrane was located in the northern margin of Gondwana, characterized by a succession of littoral-neritic clastic and carbonate rocks. From the early Triassic onwards, the tectonic evolution of the Qiangtang terrane began to change following the formation of the Indosinian orogenic belt. In the middle-late Triassic, a transgression event occurred in the Qiangtang region, and a succession of neritic-littoral carbonate and clastic rocks was deposited with a thickness ranging from several kilometers to ten-thousand meters. Nearly 9000-m-thick continental clastic and volcanic rocks of the Upper Triassic Batang Group formed in the northeastern margin (Yushu region). In the Jurassic, as a result of extension in the Bangonghu-Nujiang Ocean, the North Qiangtang terrane was transformed into a continental marginal sea, covered by 4000- to 5000-m-thick sediments (Xu et al., 2007).

In the middle Jurassic, the North Qiangtang oceanic basin continued to extend. In contrast, in the late Jurassic, widespread regression took place in the Qiangtang region, indicated by the existence of 500-m-thick Upper Jurassic neritic-littoral sedimentary rocks, which were the final trace of marine depositional facies in the Qiangtang terrane. The occurrence of late-Middle Jurassic terrestrial deposits implies that the North Qiangtang terrane began to emerge as a landmass at this time. The tectonic evolution of the entire North Qiangtang terrane was characterized by uplift, erosion and exhumation during the Cretaceous. In the Mesozoic, the North Qiangtang terrane was subject to two episodes of orogeny. Subsequently, voluminous alkaline lavas were erupted in the Kekexili region in the Miocene. Regional seismic tomographic interpretations suggest that this volcanism was associated with upwelling of a mantle diapir (Xu et al., 1999).

2.1.2 East Cimmerides (EC) in Tibet

During the Carboniferous-Permian, the South Qiangtang and the North Lhasa terranes belonged to the faunal and floral provinces of the West Cathaysides and the East Cimmerides, respectively. Opening of a branch of Neo-Tethys between the South Qiangtang and North Lhasa terranes was initiated in the Triassic after the termination of the Paleo-Tethyan regime. This Neo-Tethyan strand was closed in the early Cretaceous along the Bangonghu-Nujiang suture zone. The Lhasa terrane is subdivided into the South Lhasa and North Lhasa terranes along the Sumdo Paleo-Tethyan suture zone in central Lhasa (Yang et al., 2006).

The South Lhasa terrane is composed of a Precambrian crystalline basement, Paleozoic to Mesozoic sedimentary strata, and Paleozoic magmatic rocks. This terrane has long been accepted as the last crustal block to be accreted to Asia prior to its collision with northward drifting Indian continent in the Cenozoic (Zhang et al., 2014). Recent results have shown that the Lhasa terrane experienced multi-stage metamorphic, magmatic and tectonic events. The north Lhasa terrane includes Neoproterozoic oceanic crustal rocks, late Cryogenian (~650 Ma) high-P metamorphic units, early Paleozoic (~485 Ma) medium-P metamorphic rocks, and early Paleozoic magmatic sequences, collectively representing an Andean-type orogenic belt produced from subduction of the Paleo-Tethyan ocean floor (Zhang et al., 2014). The Songduo formation includes schists, marble and eclogite with 260 Ma high-P metamorphic and 220 Ma retrograde metamorphic ages, and is distributed in the northern margin of the South Lhasa terrane.

Voluminous Andean-type magmatism (Gangdese magmatic arc) and syn- to post-collisional volcanism took place in the Mesozoic and Cenozoic as a result of the subduction of the Neo-Tethyan oceanic lithosphere during and after the India-Eurasian collision, respectively. Plutonic and volcanic rocks associated with these magmatic events were constructed on and across the Paleo-Tethyan orogenic crust and structures. Collision-driven surficial and crustal uplift facilitated the exhumation of the root of the Andean-type magmatic arc (170-80 Ma) and of the high-T/medium-P metamorphic rocks in the northern Himalaya and southern Tibet.

2.2 Paleo-Tethyan suture zones in Tibet

Four major Paleo-Tethyan suture zones exist in Tibet. These are: Longmu Tso Shuanghu–Changning Menglian, Jinshajiang–Ailaoshan–Song Ma, East Kunlun–A’nyemaqen, and Sumdo Suture zones. We describe below these suture zones based on their formation in succession of the Paleo-Tethyan ocean basins.

2.2.1 Main Paleo-Tethyan suture zones between the East Cimmerides and West Cathaysides

Longmu Tso Shuanghu–Changning Menglian Suture Zone (LS-CMS): The curvilinear Longmu Tso–Shuanghu–Changning Menglian Suture Zone extends from the E-W striking Longmu Tso–Shuanghu suture zone in central Tibet to the N-S striking Changning Menglian suture zone in SE Tibet between the East Cimmerides and West Cathaysides (Li et al., 1995, 2006a, b; Zhong, 1998; Metcalfe, 2006, 2013; Xu et al., 2013). The Changning Menglian suture zone connects with the Inthanon and Sara Kaeo suture zones in the south (**Fig. 3**; Lepvrier et al., 2008). Considering the distinct Permian sedimentary sequences and faunal successions of the Cimmerides and Cathaysides, (Metcalfe, 2002; Zhang et al., 2013), we interpret the Longmu Tso Shuanghu–Changning Menglian suture zone as the main Paleo-Tethyan suture zone (Li, 1987; Li et al., 1995; Metcalfe, 2006; Zhang et al., 2006a, b; 2011; Zhai et al., 2011a, b).

The Paleo-Tethyan subduction system is characterized by a high-P metamorphic zone in the subduction-accretion complex along the Longmu Tso Shuanghu–Changning Menglian suture zone, as well as magmatic arc terranes, such as the Longmu Tso–Shuanghu terrane in the north and Linchang terrane in the south.

Longmu Tso Shuanghu suture zone in the northern part of the Longmu Tso Shuanghu–Changning Menglian Suture Zone: The Qiangtang terrane is divided into Northern and Southern parts, separated by a high-P metamorphic belt and ophiolites in the E-W-trending Longmu Tso–Shuanghu suture zone (LSS) (Li et al., 2006; Zhai et al., 2011a, b) in the central part of the Qiangtang terrane. This suture zone merges with the N-S-trending Changning Menglian suture zone in southeastern Tibet (**Fig. 3**). The

basement of the South Qiangtang terrane is composed mainly of 591-470 Ma orthogneisses that are unconformably overlain by Ordovician slates with a basal conglomerate and a Carboniferous classic sedimentary sequence. Thus, the basement of the South Qiangtang is similar to the Lhasa and Himalaya terranes in southern Tibet, and to the Tengchong and Baoshan terranes in southeastern Tibet (Zhao et al., 2014).

The Longmu Tso Shuanghu suture zone contains ophiolites and ophiolitic mélanges, ocean island-type basalts (OIB), high-P metamorphic rocks, Devonian-Permian radiolarian cherts, and accretionary prism complexes (Li et al., 1995; Kapp et al., 2003; Zhai et al., 2007, 2011a, b). Based on the existing U-Pb zircon ages of 467-438 Ma from a cumulate gabbro (Li et al., 2008; Zhai et al., 2010) and of 357-345 Ma from gabbro and plagiogranite rocks in the ophiolites along the Longmu Tso Shuanghu suture zone (Zhai et al., 2013a, b, c), we infer that a strand the Paleo-Tethyan Ocean existed between the North Qiangtang and South Qiangtang terranes in the Devonian-Carboniferous.

A >500-km-long, high-P metamorphic belt, composed of eclogite and blueschist, occurs in the Gemu-Gangma Tso, Shuanghu, Baqing and Jitang areas along the Longmu Tso Shuanghu suture zone (Kapp et al., 2003; Li et al., 2005, 2006; Pullen et al., 2008; Zhai et al., 2011a, b; Zhao et al., 2014). P-T calculations show that peak metamorphism in the belt took place at 2.0-2.5 GPa and 410-460°C, equivalent to a depth of 60-80 km (Zhai et al., 2011b). U-Pb zircon ages of 237-230 Ma (Zhai et al., 2011a, b) and Lu-Hf mineral isochron ages of 233-244 Ma from an eclogitic rock in the belt (Pullen et al., 2008) show that high-P rocks in this belt may have formed during the main period of subduction of the Paleo-Tethyan ocean floor. The exhumation ages of these high-P metamorphic rocks are dated by $^{40}\text{Ar}/^{39}\text{Ar}$ ages at 220 Ma for phengite separates from an eclogite, at 223-227 Ma for amphibole separates from an amphibolite, and at 222-203 Ma for mica separates from blueschist rocks (Zhai et al., 2011a,b).

A magmatic arc belt composed of volcanic rocks and dioritic plutons is exposed along the northern side of the Longmu Tso-Shuanghu metamorphic zone. These rocks have adakitic geochemical affinities and appear to have formed between 223 and 205 Ma in the late Triassic (Zhai et al., 2013a, b, c). Based on new Hf and U-Pb isotopic dating results and zircon REE analyses, Yang et al. (2011) proposed that this magmatic

belt was built as a result of northward subduction of the Paleo-Tethyan oceanic lithosphere beneath the North Qiangtang terrane in the Triassic.

The Longmu Tso Shuanghu arc terrane (LSA) is a discontinuous magmatic belt associated with an accretionary prism along the northern Longmu Tso Shuanghu suture zone. Granitic plutons in the Longmu Tso Shuanghu arc have revealed U-Pb zircon ages of 275-248 Ma (Yang et al., 2011).

2.2.2 Changning Menglian Suture Zone and its Paleo-Tethyan subduction system

The N-S-trending Changning Menglian suture zone was first recognized by Huang et al. (1984), who interpreted it as a remnant of a pre-Permian ocean basin that separated the Baoshan-Shan block (Sibumasu terrane) from the other terranes to the east. Huang et al. (1984) regarded this suture as a branch of the Jinsha-Tengliao River suture zone. The Changning Menglian suture zone is currently recognized as an important terrane boundary (**Fig. 2**) (Chen et al., 1987; Charusiri et al., 1993; Peng et al., 2006a, b; Sone and Metcalfe, 2008; Metcalfe, 2011; Jian et al., 2009; Peng et al., 2014).

The Changning Menglian suture zone contains magmatic arc and back-arc rock assemblages, an ophiolitic *mélange*, shallow marine carbonates, and a flysch unit containing Devonian-Triassic radiolarians (Feng and Liu, 1993; Feng and Ye, 1996; Feng and Zhang, 1997). It extends southward to the Inthanon and Bentong Raub suture zones (INS, BRS), which are interpreted to represent the main Paleo-Tethyan Ocean (Metcalfe, 2011). It connects to the north with the E-W-trending Longmu Tso-Shuanghu suture zone in central Tibet (**Fig. 1**). Deep oceanic sedimentary rocks in this suture zone include radiolarian cherts that range in age from the middle Devonian to the middle Triassic, and Upper Devonian and lower Carboniferous conodont faunas (Sone and Metcalfe, 2008; Metcalfe, 2011).

The Changning-Menglian ophiolite has a suprasubduction zone affinity with a U-Pb zircon age of 292 Ma. Another gabbro from this ophiolite has yielded a U-Pb zircon age of 267 Ma (Jian et al., 2009). These two ages may represent the early Permian sea-floor spreading and younger suprasubduction zone evolution of the ophiolite. This kind of multi-stage evolution of oceanic lithosphere in marginal basins has been well-

documented from the Neo-Tethyan ophiolites in the Mediterranean region (Dilek et al., 1990; Dilek and Flower, 2003; Dilek et al., 2008; Dilek and Thy, 2009; Uysal et al., 2014). The Mojiang high-P metamorphic belt associated with the Changning Menglian suture zone formed during subduction of the Changning-Menglian branch of Paleo-Tethys. Ar^{40} - Ar^{39} dating of phengite and crossitic amphibole separates from glaucophane schist in Mojiang has yielded cooling ages of 293.9 ± 0.9 Ma (Liu et al., 1989) and 279 Ma (Liu et al., 1993), respectively.

2.2.3 Jinghong, Nan-Uttaradit and Sra Kaeo suture zone (JH-NU-SKS)

The Jinghong, Nan-Uttaradit and Sra Kaeo suture zone runs parallels to the Changning-Menglian, Inthanon and Bentong-Raub suture zones (CM-IN-BRS) on the west side of the Simao-Indochina terrane. The Jinghong, Nan-Uttaradit and Sra Kaeo suture zones contain volcanic rocks, mélanges, and ophiolites, which represent a Permian back-arc basin that closed in the middle Triassic (Sone and Metcalfe, 2008; Metcalfe, 2011). The Jinghong granodioritic pluton in the eastern Lincang batholith has yielded U-Pb zircon ages of 284-282 Ma, $\epsilon_{\text{(Nd)}}$ values of -3.1 to -3.6, and initial Sr isotopic ratios of 0.709-0.710. Its geochemical and isotopic signatures are characteristic of back-arc magmas (Hennig et al., 2009).

2.2.4 Lincang-Sukhothai-Chanthaburi arc terrane

The N-S-trending Lincang arc terrane on the eastern side of the Changning Menglian suture zone lies between the Sibumasu and Indochina terranes (**Fig. 3**; Hennig et al., 2009). Previous studies have shown that the Lincang arc terrane is composed of a granitic batholith and a volcanic-sedimentary sequence. The available ages for the Lincang granites range between 282 Ma and 275 Ma Liu et al. (1989). The whole-rock Rb-Sr ages reported by Chen (1987) show a peak distribution around 297-279 Ma. However, Peng et al. (2006 a, b) have reported $^{206}\text{Pb}/^{238}\text{U}$ zircon ages of 230-229 Ma from the Lincang (LC) granites. Zircon separates from rhyolitic rocks in the northern end of the Lincang terrane have revealed a $^{206}\text{Pb}/^{238}\text{U}$ age of 231 Ma (Peng et

al., 2006a, b). It is widely accepted that the Paleo-Tethyan Changning-Menglian oceanic lithosphere was subducted eastward beneath the Lincang-Sukhothai-Chanthaburi terrane in the Permian, and that this Andean-type magmatism produced the Triassic Lincang batholith.

2.3 Jinshajiang-Ailaoshan-Song Ma suture zone and its Paleo-Tethyan subduction system

2.3.1 Jinshajiang-Ailaoshan-Song Ma suture zone

2.3.1.1 Jinshajiang-Ailaoshan Suture Zone (JSJ-ALS)

The Jinshajiang-Ailaoshan suture zone occurs between the Songpan Ganze, the North Qiangtang-Qamdo-Simao-Indochina terrane, and the South China block, and curves southward to connect with the Song Ma suture zone (Tran Van Tri, 1979; Hutchison, 1989; Lepvrier et al., 2008). It is inferred that the Jinshajiang-Ailaoshan suture zone marks a closed branch of the main Paleo-Tethyan Ocean.

The Jinshajiang suture zone lies in the northern segment of the Jinshajiang-Ailaoshan-Song Ma suture zone, and is subdivided into two branches near its center, known as the Litang suture zone in the east and the Batang suture zone in the west. The Litang suture contains meta-peridotites, cumulate rocks, mid-ocean ridge basalts (MORB), a gabbro-dike complex, chert, and deep-sea sedimentary rocks containing exotic blocks. The Batang suture zone contains MORB-type basalt, serpentinized peridotites, cumulate gabbro, doleritic dikes and radiolarian cherts (Zhang and Jin, 1979; Liu et al., 1983; Chen, 1987; Liu et al., 1990; Xu et al., 1992).

The Jinshajiang ophiolite includes a cumulate gabbro-anorthosite unit and an amphibole gabbro with crystallization ages of 338 Ma and 329-320 Ma, respectively. Jian (2008) has interpreted this ophiolite as a remnant of oceanic crust that developed in an ocean-continent transition (OCT) zone lithosphere, analogous to continental margin ophiolites (Dilek and Furnes, 2011, 2014). This ocean-continent transition zone formed in the late Devonian, during the initial rift-drift stages of the tectonic evolution of the Jinshajiang basin in Paleo-Tethys.

An ophiolitic isotropic gabbro dated at 282-285 Ma, a granite dated at 268 Ma and

a gabbro with a crystallization age of 264 Ma in an ophiolitic mélange constitute a Permian intraoceanic arc complex at the southern end of the Jinshajiang suture zone (Jian et al., 2008). The Shusong and Xuitui plagiogranites, dated at 340 Ma and 294 Ma, respectively, are part of an ophiolite massif in the Jinshajiang suture zone (Wang et al., 2000). Based on these data, we deduce that the Jinshajiang branch of Paleo-Tethys was initially formed in the Devonian. The three pre-orogenic (before T3 collision) granitoid intrusions (Zhu et al., 2011) were emplaced along the Jinshajiang suture zone at ~234-231 Ma.

Newly obtained data from the Central Ailaoshan ophiolite (CAO) indicate its igneous ages of late Devonian-early Carboniferous (~380-330 Ma). U-Pb zircon dating of two granitic plutons along the Ailaoshan suture zone has yielded the ages of ~252-248 Ma, indicating that calc-alkaline magmatism represented by these plutons occurred in the latest Permian and early Triassic (Liu et al., 2014).

2.3.1.2 Song Ma Suture Zone

The Song Ma suture zone (SMS) has been considered by many scientists as the boundary between the South China and Indochina blocks that was created by the closure of Paleo-Tethys (Tran, 1979; Lévrier et al., 2004). An ophiolite along the Song Ma suture zone is composed of serpentized peridotites, high-Al chromitites, gabbro, basaltic lavas, mafic dikes, and chert. The metabasaltic rocks and gabbros in the ophiolite and the spatially associated eclogitic rocks all exhibit MORB-type geochemical affinities (Findlay and Phan, 1997; Lévrier et al., 1997, 2004; Lacassin et al., 1998; Trung et al., 2006).

High-grade metamorphic rocks, including granulites and eclogites, have been reported from the Song Ma suture zone (Nakano et al., 2004, 2007; Osanai et al., 2004; Zhang et al., 2012). The P-T conditions of formation of the gneissic rocks are calculated as 1.9-2.0 GPa and 910-930°C. U-Pb zircon dating of pelitic gneisses surrounding a granulite block along the Song Ma suture zone has yielded an age of 233 Ma (Nakano et al., 2010). These data collectively show that the granulite facies metamorphism along the Song Ma suture zone occurred in the Carnian (early-Late Triassic).

A detailed study of an eclogite from the Song Ma suture zone has revealed the peak P-T conditions of 700°C and ~2.6 GPa. The oceanic protolith of this eclogite appears to have subducted to a mantle depth of ~85 km (Zhang et al., 2012). U-Pb SHRIMP dating of zircon from this eclogite has yielded an age of 230 Ma, which constrains the timing of westward subduction and the closure of a Paleo-Tethyan oceanic basin between the South China and Indo-China blocks as the Carnian (early-late Triassic)

2.3.2 Yidun Arc terrane related to the Jinshajiang oceanic subduction

The Yidun arc is part of a Triassic volcanic arc terrane bounded on the east by the Litang suture zone, and on the west by the Jinshajiang suture zone. This arc terrane consists mainly of volcanic rocks, intermediate to felsic intrusions, and flysch sequences (Xu et al., 1992), and is divided into six tectonostratigraphic units. These units are, from west to east: (a) Jinshajiang subduction-accretion complex, including an ophiolitic mélange, a flysch sequence, an accretionary prism complex; (b) Zhongza thrust sheet composed of Paleozoic, low-grade meta-sedimentary rocks; (c) a 244-217 Ma magmatic complex in the west (Reid et al., 2007); (d) central Yidun accretionary complex, composed of lower-middle Triassic to early upper Triassic flysch with numerous exotic blocks of limestone, sandstone and conglomerate; (e) a 215-225 Ma magmatic complex in the east (Reid et al., 2007); and (f) Gangze-Litang subduction complex (**Fig. 4A**).

2.3.3 Songpan Ganze accretionary complex

The Triassic Songpan Ganze basin is a triangular-shaped depocenter, filled with up to 10 km of sedimentary rocks, described in the literature as the Xikang Formation in the east and the Bayan Har Formation in the west. The Songpan Ganze flysch unit comprises vast accumulations of middle-upper Triassic marine gravity flow deposits, which were intruded by widespread dikes and plutons.

The Triassic sedimentary rocks of the Songpan Ganze terrane are composed of deep-sea clastic rock sequences with turbiditic textures. Abundant blocks of Carboniferous-Permian limestones crop out in the lower part of this sequence. The REE

geochemistry of the sedimentary rocks is consistent with derivation of their clastic material from an active continental margin and oceanic islands. Paleocurrent measurements in the Triassic flysch indicate transport directions from the north (East Kunlun), east (South China Block) and northwest. We infer that the oceanic lithosphere of the Paleo-Tethyan Jinshajiang basin was subducted northward, leading to the formation of a large-scale Triassic Songpan Ganze accretionary wedge, constructed between the East Kunlun, South China Block, and North Qiangtang–Qamdo–Simao–Indochina terranes. The nearly E-W-trending narrow strip represented by the Bayan Har region is composed of deep-sea turbidites with slump structures. The lower part of the Bayan Har Formation also contains numerous limestone blocks. Clastic material for the Bayan Har flysch was derived from the East Kunlun terrane to the north, as inferred from paleocurrent directions (Xu et al., 1992; She et al., 2006).

Intensely deformed, Triassic deep marine sedimentary rocks are interpreted as the trench fill of a diachronously closing, remnant ocean basin (Nie et al., 1994; Ingersoll et al., 1995; Zhou and Graham, 1996). This tectonic scenario is analogous to the proposed mechanisms for the closure of various Tethyan seaways in the eastern Mediterranean region (e.g. Mediterranean-style closure; Dilek et al., 1990; Dilek et al., 1999; Dilek and Flower, 2003; Dilek et al., 2008; Pullen et al., 2011).

2.4 East Kunlun–A'nyemaqen suture zone and its Paleo-Tethyan subduction system

2.4.1 East Kunlun–A'nyemaqen suture zone (EKL-ANMQS)

The nearly 1600-km-long, E-W-trending East Kunlun–A'nyemaqen suture zone separates the East Kunlun and Songpan Ganze terranes in northern Tibet. It extends westward across the Altyn Tagh fault to link with the West Kunlun suture zone (WKLS), which marks the boundary between the West Kunlun (WKL) and Tianshuhai (TSH) terranes. In the Dur'ngoi-Buqingshan area, the East Kunlun–A'nyemaqen suture zone contains a complete suite of ophiolitic rocks, including deformed dunite and harzburgite, cumulate mafic and ultramafic rocks, doleritic dikes, and basaltic lavas. SHRIMP U-Pb dating of zircon grains from the mafic rocks has yielded an age of 308 Ma (Yang et al., 1996). We infer that the East Kunlun–A'nyemaqen strand of Paleo-Tethys began to open

in the Carboniferous. Northward subduction of its oceanic lithosphere beneath the East Kunlun-Qaidam-Qilian terranes led to the formation of the Bulhanbuda magmatic arc at 270-185 Ma (Xiong et al., 2014) and of the west Qinling accretionary wedge at the active continental margin of the northern A'nyemaqen terrane (**Fig. 4B**; Yan et al., 2012). The accretionary complex comprises ophiolitic rocks of dunite, cumulate rocks, basaltic lavas, doleritic dikes, radiolarian chert with blocks of Carboniferous-Permian limestones, island arc volcanic rocks, and Precambrian metamorphic units.

2.4.2 Bulhanbuda arc terrane related to subduction of the East Kunlun–A'nyemaqen basin of Paleo-Tethys

The Bulhanbuda arc terrane (BAT) and the West Qinling accretionary wedge (WQLAW) are both associated with the A'nyemaqen suture zone. Thrust faults with top-to-the-south direction of tectonic transport crop out at the frontal margin of the A'nyemaqen subduction-accretion complex (**Fig. 5**). A tectonic slice of Paleozoic amphibolite occurs in the central part of the complex. There is a detachment surface between the middle and lower Triassic flysch units, which were deposited in a backarc basin developed above a north-dipping subduction zone.

The Bulhanbuda arc terrane contains widespread, late Permian-late Triassic granitoid plutons and volcanic sequences (Harris et al. 1988; Mock et al. 1999; Mo et al., 2007; Xu et al., 2007). All of these arc rocks are characterized by low K_2O/Na_2O ratios (0.35-0.87), high Mg# (37-55), significant depletion of HFSE (high field strength elements), and enrichment in Rb, Ba and K. The granitic magmatism appears to have lasted from 270 Ma to 185 Ma, with peak ages around 252 Ma, 240 Ma and 226 Ma (Chai et al., 1984; Xu et al., 1990; Ma et al., 2011), whereas volcanism seems to have taken place in two stages, i.e., late Permian to early Triassic (262-240 Ma) and late Triassic (230-210 Ma). In general, the late Permian - early Triassic granitoids occur mainly in the southern part of the terrane, whereas the middle Triassic - early Jurassic granitoids largely crop out in the northern part (**Fig. 5**).

Following the emplacement of the late Permian-early Triassic granitoids and construction of the arc complex, the A'nyemaqen basin within Paleo-Tethys closed in the

Middle Triassic leading to an arc-continent collision. Post-collisional magmatism, facilitated by slab break-off, produced high-silica adakitic granitoids (230-185 Ma, e.g., Xiong et al., 2014), and was accompanied by focused extensional deformation and sedimentary basin development within the East Kunlun ocean basin. The overthickened orogenic crust also underwent partial melting, producing S-type granites.

2.4.3 West Qinling accretionary wedge related to subduction of the A'nyemaqen basin

The triangular-shaped West Qinling accretionary complex is bounded by the Zhongwulong ophiolite belt in the northeast and by the A'nyemaqen ophiolite in the south. The Zhongwulong ophiolite consists of upper mantle peridotites, gabbros, doleritic dikes, chert and basaltic pillow lavas. Mafic dikes from this ophiolite have revealed Rb-Sr isochron ages of 318 ± 3 Ma (Wang et al., 2001). A gabbro sample from the Zhongwulong ophiolite dated by the LA-ICP-MS U-Pb zircon method has yielded an age of 250 Ma (Wang et al., 2007), and calc-alkaline volcanic rocks from the southern side of the accretionary complex have yielded ages ranging from 246 Ma to 238 Ma (**Fig. 6**) (Zhang et al., 2007; Guo et al., 2009). The Triassic West Qinling accretionary complex developed as a result of northward subduction of the oceanic lithosphere of the E-W-trending, East Kunlun–A'nyemaqen basin within Paleo-Tethys (Jiang et al., 1996).

2.5 Sumdo suture zone and its Paleo-Tethyan subduction system

2.5.1 Sumdo Suture zone (SDS)

The Carboniferous-Permian Sumdo suture zone lies in the central Lhasa terrane, where it separates the South Qiangtang-North Lhasa terrane from the South Lhasa terrane (Bureau of Xizang Geological and Resources Survey, 1993; Yang et al., 2007). It is marked by ophiolites and an E-W- trending, nearly 100-km-long Sumdo eclogite belt (Fig. 7), which occurs as tectonic slices in a garnet-bearing, mica-quartz schist and amphibolites (Yang et al., 2006). The protolith of these metamorphic rocks was a flysch sequence, which is known as the Sumdo Formation.

Pressure-temperature calculations of the eclogitic rocks have yielded peak

metamorphic conditions of 2.7 GPa and 730°C, close to the phase boundary between coesite and quartz. Geochemical data suggest that protolith of the eclogitic rocks was mid-ocean ridge basalt (MORB), derived from the depleted upper mantle of Paleo-Tethys (Yang et al., 2006; Chen et al., 2009, 2010). U-Pb SHRIMP dating of zircon separates from the eclogitic rocks has yielded an average metamorphic age of 262 ± 5 Ma, which is interpreted to reflect the timing of Paleo-Tethyan oceanic subduction.

Amphibolite-facies metamorphic rocks at Nyainqentanglha consist mainly of gneiss, amphibolite, quartz schist and marble, and occur as blocks in the western Sumdo high-P metamorphic complex. Metamorphic zircons from the Nyainqentanglha amphibolite, which was produced by retrograde metamorphism of the Sumdo eclogite in the Triassic, have yielded concordant $^{206}\text{Pb}/^{238}\text{U}$ ages of 225-213 Ma (Dong et al., 2011). These rocks, together with the eclogitic units, represent a nearly 300-km-long, E-W-trending, Permo-Triassic metamorphic belt.

Muscovite separates from muscovite-quartzite schist in the Sumdo Formation have yielded $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages of 240-220 Ma, similar to the ages obtained from muscovite and amphibole separates from the eclogite belt (240-220 Ma) (Li et al., 2009). We interpret these ages to mark the timing of the orogenic deformation and metamorphism.

2.5.2 Sumdo Paleo-Tethyan accretionary wedge

Structures within the Sumdo Formation include E-W-striking, ductile thrust faults with top-to-the-north sense of shearing, south-dipping foliation planes, 'A'-type folds and mylonitic textures (Li et al., 2009). Brittle thrust faults with top-to-the-south sense of shearing are superimposed on these previously formed ductile structures (**Fig. 7**). Granitic plutons that are 240-190 Ma in age are intrusive into various metamorphic units of the Sumdo Formation.

Medium-pressure amphibolites formed in the western segment of the Sumdo high-P metamorphic complex in the Norian (225-213 Ma; Dong et al., 2011), followed by the formation of high-T metamorphic rocks in the eastern segment during the latest Triassic-early Jurassic (~204-192 Ma; Lin et al., 2013). The Sumdo accretionary complex makes

up a ~300-km-long and 50-km-wide zone in the eastern part of the Central Lhasa terrane that developed during a late Triassic, collisional orogen. Syn- to post-collisional granites (223-190 Ma) are intrusive into this accretionary complex (Li et al., 2009).

3. Paleo-Tethys system and collisional orogens of the passive margins of the Yangtze block

Orogenic deformation during plate collisions is not limited to narrow plate boundaries, and may extend into plate interiors, far from collision fronts. Amalgamation of multiple continental blocks within an oceanic realm, such as in the Melanesian region in the SW Pacific Ocean, may lead to construction of an orogenic collage with widths of hundreds or even thousands of kilometers. The Paleo-Tethyan mountain belt in Tibet is a good example of such an orogenic collage, extending nearly 5200 km along its E-W length and 2500 km across its N-S width, and it is thus an excellent natural laboratory to study the processes of an accretionary orogen buildup (Xu et al., 2007, 2012, 2013). The Paleo-Tethyan mountain belt in Tibet that formed during the collision of the East Cimmerides and the West Cathaysides is connected in the east with the Qinling-Dabie-Sulu-Ogcheon orogenic belts between the North and South China blocks.

3.1 Paleo-Tethyan system on the western margin of the Yangtze block

The Jinshajiang-Ailaoshan-Song Ma suture zone occurs between the North Qiangtang-Simao-Indochina terrane, South China block, and the Songpan Ganze terrane. Studies have shown that the Jinshajiang-Ailaoshan-Song Ma Paleo-Tethyan oceanic slab was subducted westward beneath the North Qiangtang-Simao-Indochina terrane along the Jinshajiang and Ailaoshan-Song Ma trenches, producing the Yidun and Song Ma arc terranes.

The Emeishan large igneous province, located in the SW margin of the South China block, comprises a bimodal mafic-silicic suite with the silicic rocks occurring in the uppermost part of a thick lava sequence. The silicic rocks have ages of 257-263 Ma, and display rather uniform $\epsilon_{(Nd)}$ values (+1 to +2.9) that are comparable with those of

uncontaminated, high-Ti basalts (Xu et al., 2010). The geochemistry of these bimodal lavas reveals that at least two different mantle source components were involved in their melt evolution: an enriched mantle and a depleted mantle.

We infer a subduction model for the Jinshajiang-Ailaoshan Paleo-Tethyan slab in a ‘trench-ridge-trench’ triple junction configuration. Regional studies show that the Jinshajiang-Ailaoshan-Song Ma Paleo-Tethyan oceanic slab was subducted westward beneath the North Qiangtang-Simao-Indochina terrane along the Jinshajiang-Ailaoshan trenches, along with a Permian Emeishan basaltic buildup on the western margin of the Yangtze block. The South China block included the South Qinling terrane along its northern margin and the Songpan-Ganze terrane on its northwestern margin prior to the collision between the South China block, North China block, and Indochina terranes. The passive margins of the South China block were involved in the Triassic collisional events that developed decollement-type orogens (**Fig. 8**).

3.2 Decollement-type orogens of the northern and northwestern margins of the South China block

3.2.1 Decollement orogen in the Songpan Ganze terrane, NW margin of the South China block

The Songpan Ganze terrane is a triangular-shaped, Paleo-Tethyan collisional orogen, which is separated from the East Kunlun terrane to the north by the A'nyemaqen suture zone, from the South China Block to the east by the Longmenshan thrust fault, and from the North Qiangtang terrane to the southwest by the Jinshajiang suture zone. It is composed of a Neo-Proterozoic basement and Paleozoic cover sequences, which include Sinian volcanic meta-conglomerate, sandstone, marble, quartzite and quartz-schist, Ordovician marble and limestone interlayered with quartzite and mica-schist, Silurian limestone, Devonian dolomite and limestone interlayered with phyllite, Carboniferous limestone, and Permian basalt interlayered with carbonates in the eastern part of the Songpan Ganze terrane.

The eastern Songpan Ganze terrane is characterized by widespread magmatic rocks, which formed above two separate subduction zones during the mid to late Triassic.

These two subduction systems led to the closure of Paleo-Tethys and to the development of the Kunlun-A'nyemagen suture to the north and the Jinsha-Litang suture to the south.

Plutons in the western Songpan Ganze terrane have yielded U-Pb zircon ages ranging from 225 to 193 Ma. $^{40}\text{Ar}/^{39}\text{Ar}$ analyses of muscovite separates from the Hudongliang and Zhuonai Lake plutons have yielded the ages of 210.7 ± 2.5 Ma and 212.7 ± 2.5 Ma, respectively. These plutonic rocks can be subdivided into two distinct geochemical groups: the 221-212 Ma plutons are composed of high-K, calc-alkaline granitoids that were likely derived from partial melting of the downgoing Paleo-Tethyan oceanic slab and its overlying marine sediments (Zhang et al., 2014). The 225-193 Ma plutons (Daheishan, Yunwuling, Zhuonai Lake, Malanshan and Hudongliang) were produced by partial melting of juvenile crust. Collectively, these data suggest that the Hoh-Xil turbiditic sequences of the Songpan Ganze basin are underlain by continental arc crust, which is more widespread than previously thought.

A large-scale, south-verging, décollement zone separates the Neo-Proterozoic basement in the Yangtze block from the Sinian-Triassic cover sequences in the eastern Songpan Ganze terrane (Malavielle et al., 1991; Mattauer et al., 1992; Xu et al., 1992; Calassou, 1994; Roger et al., 2004; Harroufield and Wilson, 2005). This décollement zone is about 2-3 km thick, and is characterized by a shear zone with a well-developed mylonitic foliation and a nearly N-S trending stretching lineation. Foliation planes are steeply dipping higher up in the upper parts of the cover sequences and subhorizontal to gently dipping in the lower Sinian-Triassic sequences below. The high temperature ($>650^\circ\text{C}$) fabric and numerous granitic veins within the shear zone developed as a result of the south-vergent, thick-skinned thrust faulting and folding during the Indosinian Orogeny (~ 230 -200 Ma). This deformation led to crustal thickening and shortening of the Songpan Ganze terrane. Barrovian-type metamorphic mineral assemblages characterized by sillimanite ($T > 600$ - 700°C), kyanite-staurolite ($T = 550^\circ$ - 570°C), Fe-Al-bearing garnet ($T = 500^\circ$ - 540°C), and biotite ($T = 400^\circ$ - 500°C) are associated with the shear zone fabrics, indicating crustal depths of >15 -20 km for their origin around 220-190 Ma (Xu et al., 1992; Huang et al., 2003; Zhou et al., 2008).

Partial melting of the overthickened orogenic crust produced syn-collisional, I-type granitic intrusions with ages of 225-190 Ma (Xu et al., 1992; Roger et al., 1995,

1997, 2004; Zhang et al., 2006, 2007; Reid et al., 2007; Xiao et al., 2007; Weislogel, 2008), and post-collisional, S-type granites with ages of 200-150 Ma and 153-105 Ma (Roger et al., 2004; Reid et al., 2007). Along the southern front of the décollement, the basement rocks were uplifted and thrust onto the Paleozoic sedimentary strata. Subsequent N–S-oriented crustal contraction migrated from the north to south, and produced localized deformation associated with refolding of the Danba and Muli antiforms (**Fig. 9**).

Similar to the South Qinling orogenic belt, the east Songpan Ganze is a Triassic décollement orogen with top-to-the-south sense of shearing (**Fig. 10**; Xu et al., 1986, 1992, 2012, 2013). The only significant difference between the two is that the Songpan Ganze terrane represents a high-temperature collisional orogen, whereas the South Qinling orogenic belt is mainly a low-temperature mountain belt.

3.2.2 Décollement orogen in the South Qinling terrane along the northern margin of the South China block

The South Qinling orogenic belt is bounded by the Proto-Tethyan Danfen suture zone in the north and the curvilinear Daba foreland thrust belt in the south. It includes a large-scale, décollement shear zone between the Neo-Proterozoic basement and the Sinian-Triassic cover (**Fig. 10**).

A well-developed, mylonitic foliation, ~N-S-trending stretching lineation and sheath folds are observed in the top part of the Precambrian basement. Microstructures and quartz lattice-preferred orientations (LOPs) in the mylonitic rocks indicate top-to-the-south sense of shearing under low temperatures (<400-450°C). Structures in the Sinian to Lower-Middle Triassic cover sequence are characterized by recumbent to gentle folds dipping to the north and upright folds that dip steeply to the north. Phengite separates from medium-pressure amphibolitic rocks in the décollement zone have revealed an $^{40}\text{Ar}/^{39}\text{Ar}$ cooling age of 232 Ma, whereas Na-feldspar grains from the same sequence have yielded an age of 216 Ma (Xu, 1987a, b).

4. Discussion

4.1 Tectonic framework of the East Cimmerides and West Cathaysides in Tibet

The Paleo-Tethyan tectonics in Tibet involves the formation of ophiolites and ophiolitic mélanges, island arc and magmatic arc complexes, high-pressure metamorphic belts, and accretionary wedges containing numerous exotic blocks. These units mark suture zones, which separate Gondwana-derived terranes that were accreted into Asia during the late Paleozoic and Mesozoic (e.g. Carter et al., 2001; Metcalfe, 2002, 2006, 2011, 2013). The Devonian Longmu Tso-Shuanghu-Changning Menglian suture zone is the main boundary between the West Cimmerides and East Cathaysides; the other suture zones represent the closure sites of marginal basins within Paleo-Tethys (Lepvrier et al., 2008).

The East Cimmerides and the West Cathaysides in Tibet contain six major terranes, including East Kunlun, Songpan Ganze, North Qiangtang-Qamdo-Simao-Indochina, South Qiangtang-Baoshan-Sibumasu, North Lhasa-Tengchong and South Lhasa. There are five ophiolite belts (East Kunlun-A'nyemaqen, Ganze-Litang, Jinshajiang-Ailaoshan-Song Ma, Longmu Tso/Shuanghu-Changning/Menglian and Jinghong) associated with the major suture zones and five volcanic arcs (Bulhanbuda, Yidun, Longmu Tso- Shuanghu, Lincang-Sukhothai and Sumdo). In addition, there are four accretionary wedges (West Qinling, Bayan Har-Songpan Ganze, Shuanghu-Nierong-Jitang and Sumdo), and four high-P metamorphic belts (Song Ma, Longmu Tso-Shuanghu, Mojiang and Sumdo).

The subduction polarities of the multiple Paleo-Tethyan oceanic slabs differed during the late Paleozoic-Early Triassic evolution of Paleo-Tethys. We can infer the subduction polarities based on the kinematics of structures preserved within deformed rocks associated with the suture zones, the orientations of paired metamorphic zones in the orogenic belts, and the occurrence and geochemistry of volcanic rocks on either side of the ophiolitic belts.

The E-W-trending East Kunlun-A'nyemaqen oceanic slab was subducted northward beneath the East Kunlun terrane in northern Tibet, whereas the Sumdo oceanic slab was subducted northward beneath the North Lhasa terrane in southern Tibet. The Longmu Tso Shuanghu-Changning Menglian ophiolites indicate eastward

subduction of a Paleo-Tethyan oceanic slab beneath the North Qiangtang-Qamdo-Simao-Indochina terrane in central Tibet.

The southern Jinshajiang-Ailaoshan-Song Ma oceanic slab may have been subducted westward beneath the North Qiangtang-Qamdo-Simao-Indochina terrane. However, the tectonic setting of the Yidun arc in the central Jinshajiang-Ailaoshan-Song Ma suture zone and the related structural evidence suggest that subduction along the Jinshajiang component of this suture zone was to the east. Subduction along the Ganze-Litang suture zone was, on the other hand, apparently to the west. The subduction polarity on the Jinshajiang suture zone has been interpreted differently by different authors. Xu et al. (1992) and Mo et al. (1994) proposed eastward subduction, whereas Reid et al. (2005a, b) argued for west-dipping subduction. Therefore, the relationship between the observed structures and the subduction polarities across the Yidun arc are still unresolved, and have been interpreted differently in models of the Ganze-Litang and Jingshajiang suture zones.

4.2 Genesis of the Longmu Tso Shuanghu-Changning Menglian *mélange*

Two different interpretations have been presented for the formation of the Longmu Tso-Shuanghu *mélange*: an *in-situ* or autochthonous model and an allochthonous model. The *in-situ* model is based on reports that the E-W-trending Longmu Tso-Shuanghu suture zone, which contains high-P metamorphic rocks and an ophiolitic *mélange*, separates the Upper Paleozoic strata containing warm-water fauna of a Cathaysian affinity in the north Qiangtang terrane from the strata in the south that contain cold-water fauna of a Gondwana affinity (Li et al., 2005, 2006; Zhai et al., 2011a, b). The N-S-trending Changning-Menglian suture zone, which is the southern segment of the Longmu Tso-Shuanghu-Changning Menglian suture zone, also contains an ophiolitic *mélange*, magmatic arc rocks, backarc-basin deposits, and a deep-sea flysch unit. The flysch in this zone contains Devonian-Triassic radiolarians (Feng and Liu, 1993; Feng and Ye, 1996; Feng and Zhang, 1997). These sutures clearly represent important terrane boundaries as inferred from the occurrence of highly different Carboniferous-Permian sedimentary sequences and faunal successions on their opposite sides (Metcalf, 2002;

Sone and Metcalfe, 2008; Matcalfe, 2011; Zhang et al., 2013).

The allochthonous model suggests that the Longmu Tso-Shuanghu mélange was underplated southward beneath the Qiangtang terrane during the early Mesozoic by flat subduction of the Songpan Ganze oceanic lithosphere (Kapp et al., 2000; Pullen et al., 2011). The Longmu Tso-Shuanghu mélange is distributed for ~200 km along the Jinshajiang suture zone and includes metamorphic mineral assemblages indicating P-T conditions of their formation around 60-80 km at depth in a subduction zone (Zhai et al., 2011b). We find this evidence incompatible with a flat subduction interpretation, and hence favor the autochthonous model.

4.3 Interpretation of the Paleo-Tethyan Sumdo suture zone in southern Tibet

Permian marine deposits in Tibet crop out in an array of blocks where they contain diverse faunas of diverse biogeographical affinities. The North Qiangtang-Qamdo terrane contains Permian marine fauna of a typical Cathaysian affinity, whereas the Himalayan stratigraphic units are characterized primarily by cold-water faunas with only limited warm-water immigrants. The intervening South Qiangtang and Lhasa terranes are ascribed to the Cimmerian, which is characterized by mixed warm- and cold-water fauna, supplemented by a strong endemic component (Zhang et al., 2013). Thus, we suggest that the South Qiangtang and Lhasa terranes constituted a single block before the opening of the Bangonghu-Nujiang strand of the Neo-Tethyan Ocean.

The Sumdo suture zone, which is composed of ophiolites, high-P eclogites, arc volcanic rocks, and an accretionary wedge complex, is a newly discovered Paleo-Tethyan suture in the South Qiangtang-Lhasa terrane (Yang et al., 1998). The oceanic lithosphere of the Sumdo branch of Paleo-Tethys was subducted northward beneath the North Lhasa terrane prior to the development of this suture zone.

4.4 Tectonic model for the evolution of Paleo-Tethyan and Triassic orogens in Tibet

The main stages of the tectonic evolution of Paleo-Tethys and of the Paleozoic-Triassic orogenic belts are depicted in **Figure 11** and are summarized below.

(1) *Opening of Paleo-Tethys*: Paleo-Tethys was initially opened in the Devonian-Carboniferous, leading to the formation of continental margin and MOR-type of oceanic lithosphere (Dilek and Furnes, 2011, 2014). The remnants of these lithospheric types are preserved in the Longmu Tso Shuanghu-Changning Menglian ophiolite belt between the East Cimmerides and the West Cathaysides. The Jinshajiang-Changning Menglian (~380-330 Ma), East Kunlun-A'nyemaqen (~308 Ma) and Sumdo ophiolites (~305 Ma) represent the remnants of various strands of the main Paleo-Tethyan Ocean between the East Kunlun and Songpan Ganze terranes, the Songpan Ganze and North Qiangtang-Qamdo-Simao-Indochina terranes, and the South Qiangtang/Lhasa-Tengchong/Baoshan-Sibumasu terranes, respectively.

(2) *Early subduction stage of Paleo-Tethyan oceanic slabs*: The oceanic lithosphere of the East Kunlun-A'nyemaqen basin was subducted northward beneath the East Kunlun terrane, forming the Bulhanbuda arc terrane in northern Tibet around 270-185 Ma. The Sumdo oceanic slab was subducted northward beneath the North Lhasa-South Qiangtang terrane, developing a Carboniferous-Permian volcanic arc in southern Tibet.

In Southeast Tibet, the oceanic lithosphere of the Changning Menglian branch of Paleo-Tethys was subducted eastward beneath the Indochina terrane, producing the Mojiang high-P metamorphic belt (294 Ma) and the Lincang arc terrane (**Fig. 11B**). Formation of this arc terrane overlapped with seafloor spreading in the Jinghong backarc basin (282-264 Ma). The Jinshajiang-Ailaoshan-Song Ma oceanic slab was then subducted westward beneath the Qamdo-Simao-Indochina terrane. Meanwhile, the Emeishan bimodal, mafic-silicic volcanic suite developed along the western rifted margin of the South China block during the late Permian (257-263 Ma). The Emeishan magmatic event is considered to have emanated from a deep mantle plume that produced widespread volcanic rocks (**Fig. 11B**).

In Central Tibet, the ocean floor of the Longmu Tso Shuanghu branch of Paleo-Tethys was subducted northward beneath the North Qiangtang terrane. This subduction process produced a magmatic arc during ~275-248 Ma.

(3) *Late subduction stage of Paleo-Tethyan oceanic slabs*: Subduction of Paleo-Tethyan

oceanic slabs continued in the Triassic, as recorded in the West Qinling accretionary wedge, the Yidun arc (227-218 Ma), the Longmu Tso-Shuanghu arc terrane (220-205 Ma) and the high-P metamorphic belts of the Longmu Tso Shuanghu (244-238 Ma) and Song Ma (232Ma) suture zones. The Mojiang and Sumdo high-Pressure metamorphic zones were formed during an early subduction stage and were then exhumed to shallow depths in a subduction channel. The Jinghong back-arc basin was closed in the Middle Triassic, leading to an arc-continent collision (**Fig. 11C**).

(4) *Final closure of Paleo-Tethys and terrane amalgamation*: Closure of the multiple branches of the Paleo-Tethyan Ocean resulted in terrane amalgamation and development of a large orogenic collage in Tibet during the latest Triassic-Jurassic. The geological record of this collage reflects the rift-drift, seafloor spreading, subduction zone, and collision tectonics of the Paleo-Tethyan realm and the continental blocks within and around this Pacific-type, complex oceanic domain.

5. Conclusions

The Paleo-Tethyan geology of Tibet involves multiple terranes, suture zones containing ophiolites and ophiolitic mélanges, high-P metamorphic belts, magmatic arcs, and accretionary prism complexes that largely developed during the Paleozoic-early Mesozoic. This Paleo-Tethyan realm is subdivided into two main domains based on the existence of diverse Permian sedimentary sequences and faunal successions: the East Cimmerides to the west and the West Cathaysides to the east. The Devonian Longmu Tso Shuanghu-Changning Menglian suture zone separates these two main domains. The other suture zones in Tibet represent the sites of closure of the multiple strands of the main Paleo Tethyan Ocean.

Subducting Paleo-Tethyan oceanic slabs had different polarities during the late Paleozoic-early Triassic evolution of this ocean, which had a complex paleogeography. The East Kunlun-A'nyemaqen oceanic slab was subducted northward beneath the East Kunlun terrane in northern Tibet, whereas the Sumdo oceanic slab was subducted northward beneath the South Qiangtang-North Lhasa terrane in southern Tibet. The

structural architecture and the geochemical fingerprints of the Longmu Tso Shuanghu-Changning Menglian and Jinshajiang-Ailaoshan-Song Ma ophiolite belts indicate that Paleo-Tethyan oceanic slabs were subducted in opposite directions (westward and eastward) beneath the North Qiangtang-Qamdo-Simao-Indochina terrane in central Tibet. The model for the Jinshajiang-Ailaoshan-Song Ma oceanic slab suggests its westward subduction beneath the North Qiangtang-Simao-Indochina terrane along the Jinshajiang and Ailaoshan-Song Ma trenches in a trench-ridge-trench triple junction configuration. The Permian Emeishan volcanic field marks a zone of discrete volcanism and associated rifting on the western margin of the South China Block that was fed by a mantle plume beneath the Paleo-Tethyan realm.

Multiple collision events between various Paleo-Tethyan terranes in Tibet produced a vast Indosinian orogenic collage during the latest Triassic-Jurassic. This crustal collage has been affected by post-Jurassic to Cenozoic deformation that produced a crustal-scale shear zone and décollement between the Precambrian basement and the cover sequences, regional thrust faults and folds, and strike-slip fault zones.

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Figure Captions

Figure 1. Paleogeographic reconstructions of the Tethyan region for late Permian (A) and late Triassic (B), showing relative positions of the west and southeast Asian terranes and distribution of the landmasses and sea during these time periods (after Scotese, 2004).

Key to lettering: SC-South China; I-Indochina; NC-North China; SB-Sibumasu; WB-West Burma; QT-Qiangtang; L-Lhasa; WC-Western Cimmerian Continent, SG-Songpan Ganze.

Figure 2. Schematic Permian paleogeographic reconstruction of northern Peri-Gondwana and Paleo-Tethys with a focus on the crustal blocks in Tibet. A. Samarian; B. Artinskian; C. Capitanian; D. Changhsingian (after Metcalfe, 2002).

Tectonic blocks: Ar-Arabia; B-Baoshan; IC-Indochina; Ir-Iran; L-Lhasa; SC-South China; Qi-Qiangtang; SB-Sibumasu; SA-South Afghanistan; SP-South Pamir; CP-Central Pamir; Qa-Qamdo; T- Tengchong; Si- Simao; Tu-Turkey; H-Himalaya.

Figure 3. Simplified tectonic map with age data, showing the Paleo-Tethyan system in the East Cimmerides and West Cathaysides in Tibet (Sources of the age data: Triassic granitoids in SPGZ are from Roger et al., 2004; Zhang et al., 2006; and Yuan et al., 2010).

Blocks and terranes: NCB: North China Block; SCB: South China Block; TRMB: Tarim Block; IDB: India Block; EKL-QDM-QL: East Kunlun-Qaidam-Qilian terrane; WKL: West Kunlun terrane; SPGZ: Songpan-Ganze terrane; NQT-QD-SM-IC: North Qiangtang-Qamdo-Simao-Indochina terrane; SQT-BS-SB: South Qiangtang-Baoshan-Sibumasu terrane; NLS: North Lhasa terrane; SLS: South Lhasa terrane; TC: Tengchong terrane; TSH: Tianshuihai terrane; WB: West Burma terrane.

Suture zones: EKL-ANMQS: East Kunlun-A'nyemaqen Suture; WKLS: West Kunlun Suture; LTS: Litang Suture; JSJ-ALS-SMS: Jinshajiang-Ailaoshan-Song Ma Suture; LS

-CM-INS: Longmu Tso Shuanghu-Changning Menglian-Inthanon Suture; JH-NU-SKS: Jinghong-Nan Uttaradit-Sra Kaeo Suture; BNS: Bangonghu-Nujiang Suture; SQH-JLS: Siquanhe-Jiali Suture; SDS: Sumdo Suture; ITS: Indus-Tsangbo Suture; WQL: West Qinling; YD: Yidun Arc.

Arc terranes: BHDA: Bulhanbuda Arc terrane; YDA: Yidun Arc terrane; LC-ST-CBA: Lincang-Sukhothai-Chanthaburi Arc terrane; KHA: Kohistan Arc terrane; LDA: Ladakh arc terrane; WQL: West Qinglin terrane

Faults: ALTF: Altyn Tagh Fault; NQLT: North Qilian Thrust; LMST: Longmenshan Thrust; RRF: Red River Fault; KKF: Karakorum Fault; MFT: Main Frontal Thrust; SGF: Sagaing Fault; GLGF: Gaoligong Fault.

Figure 4. Cross-sections of the Yidun Arc Terrane (4A), and the A'nyemaqen Suture Zone (4B).

Figure 5. Simplified geological map of the Bulhabuda magmatic arc terrane at the northern active margin of the East Kunlun-A'nyemaqen branch of the Paleo-Tethyan Ocean.

Figure 6. Tectonic map of the West Qinling accretionary prism complex north of the A'nyemaqen suture zone.

Figure 7. Simplified tectonic map of the Sumdo subduction complex in the South Qiangtang-Lhasa terrane.

Figure 8. Simplified tectonic map showing the Paleo-Tethyan system and the Triassic orogens along the western and northern margins of the South China Block.

Key to lettering: ELK-QDM-QL-NQL: East Kunlun-Qaidam-Qilian-North Qinling terrane; NCB: North China Block; SPGZ: Songpan Ganze terrane; SQL: South Qinling Orogen; NQT: North Qiangtang; QD: Qamdo; SM: Simao; IC: Indochina; SQT-NLS: South Qiangtang-North Lhasa; SLS: South Lhasa; HM: Himalaya; TC-BS: Tengchong-Baoshan; SB: Sibumasu; EKL-ANMQS: East Kunlun-A'nyemaqen Suture; LM-CMS:

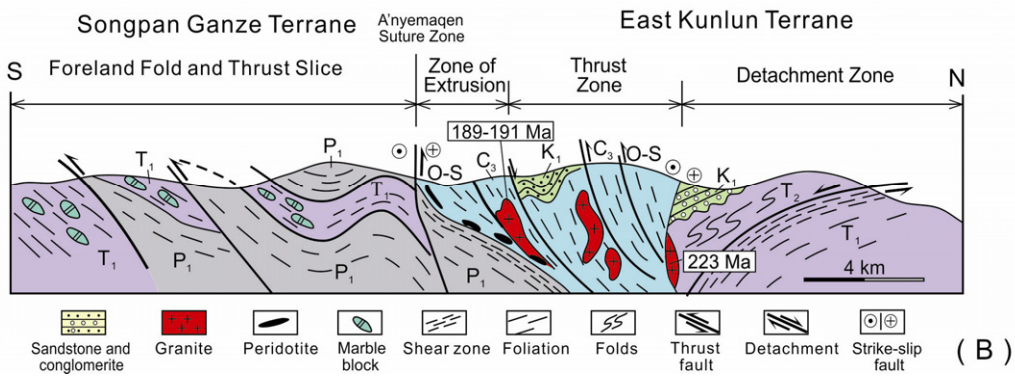
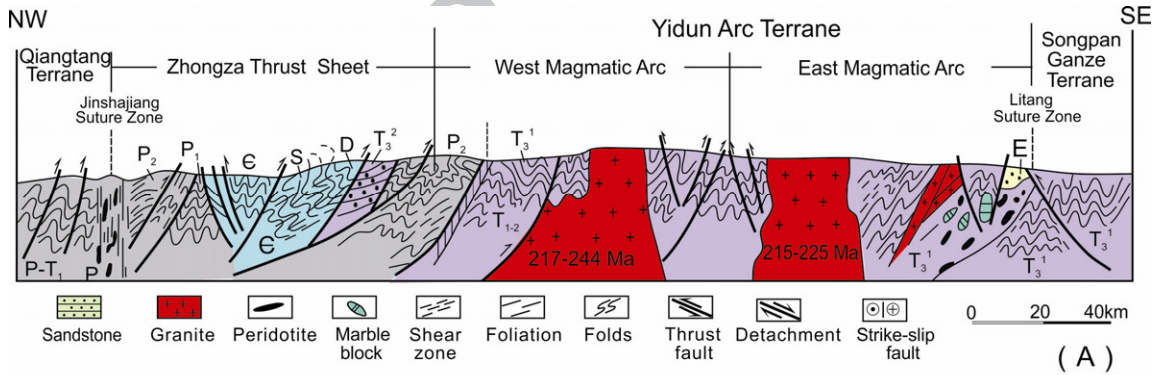
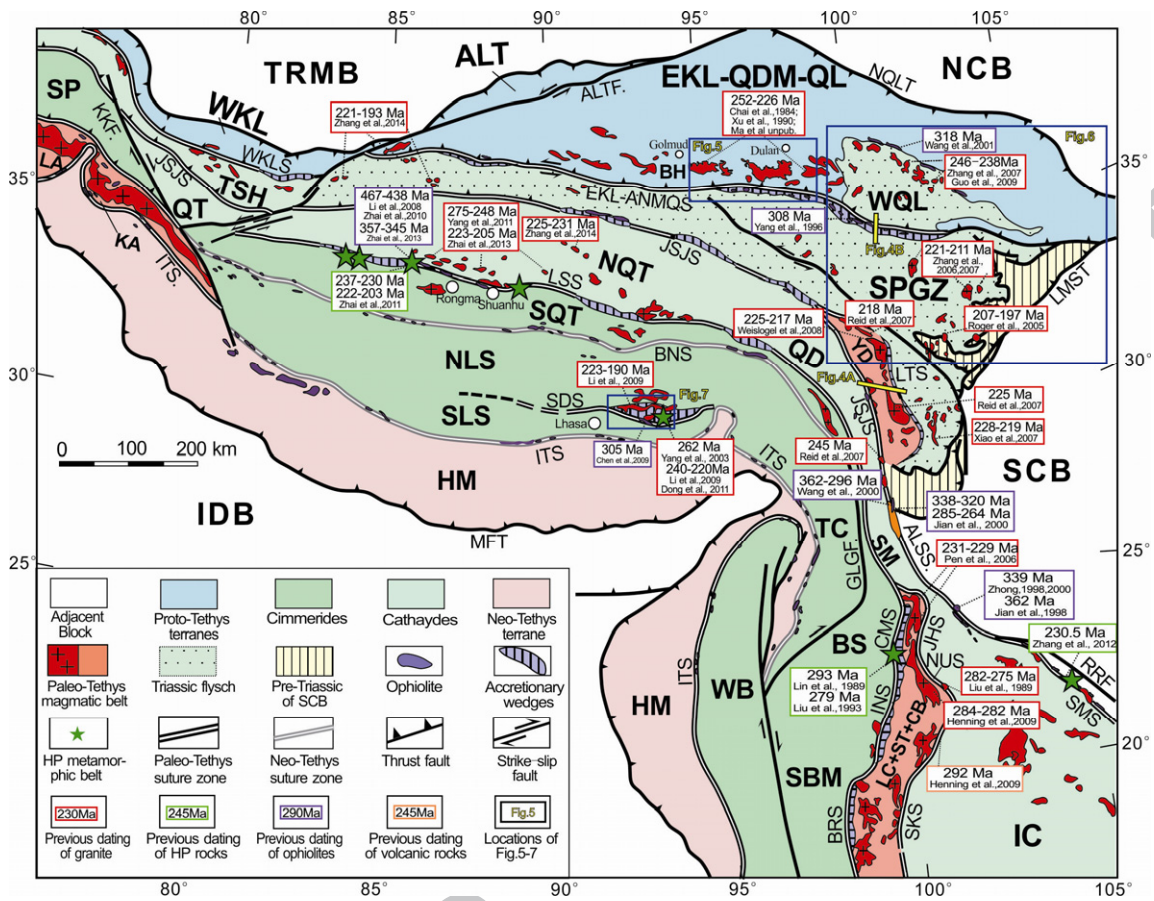
Longmu Tso Shuanghu-Changning Menglian Suture; JH-Jinghong Suture; SDS: Sumdo Suture; BNS-Bangonghu Nujiang Suture; ITS: Indus-Tsangpo Suture; SQL: South Qinling terrane; SPGZ: Songpan Ganze terrane; NV: North Vietnam terrane.

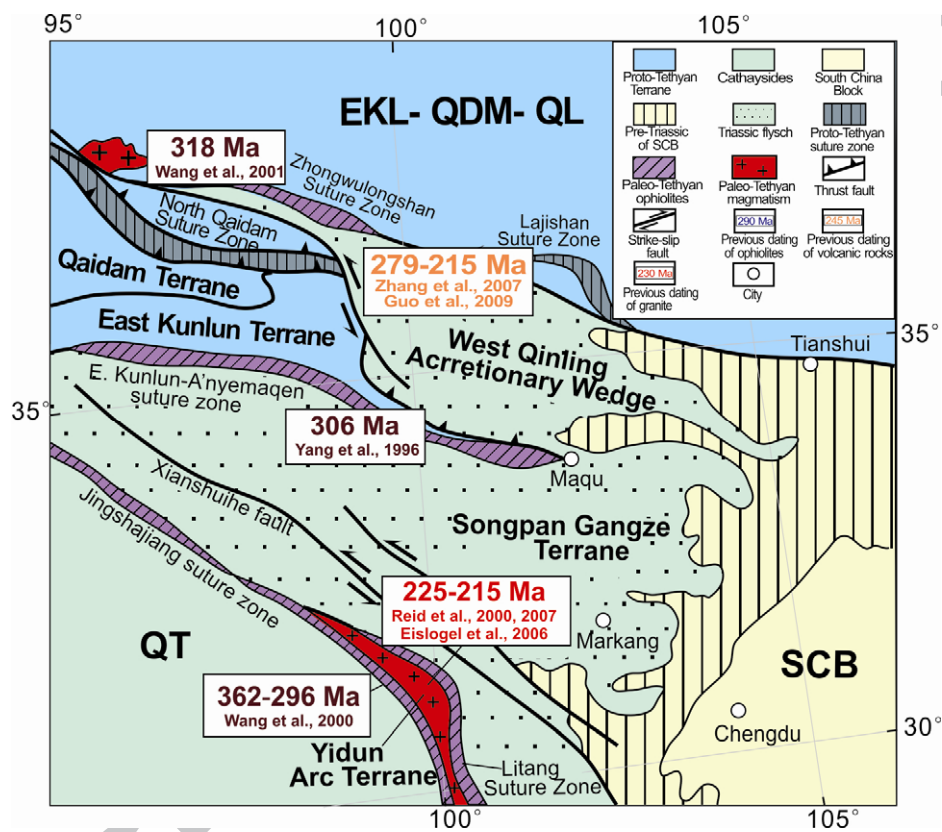
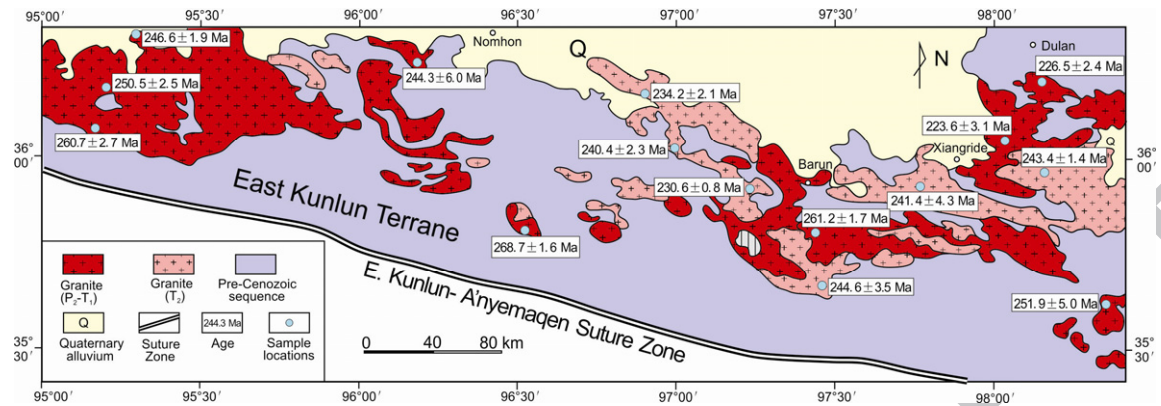
Figure 9. Schematic Tectonic Map (A), and cross-section (B) of the Songpan-Ganze orogen in the northwestern South China block. Key to lettering: Bi-biotite; Ch-chlorite; Ky-kyanite ; Ga-garnet; Sil-sillimanite ; St-staurolite;

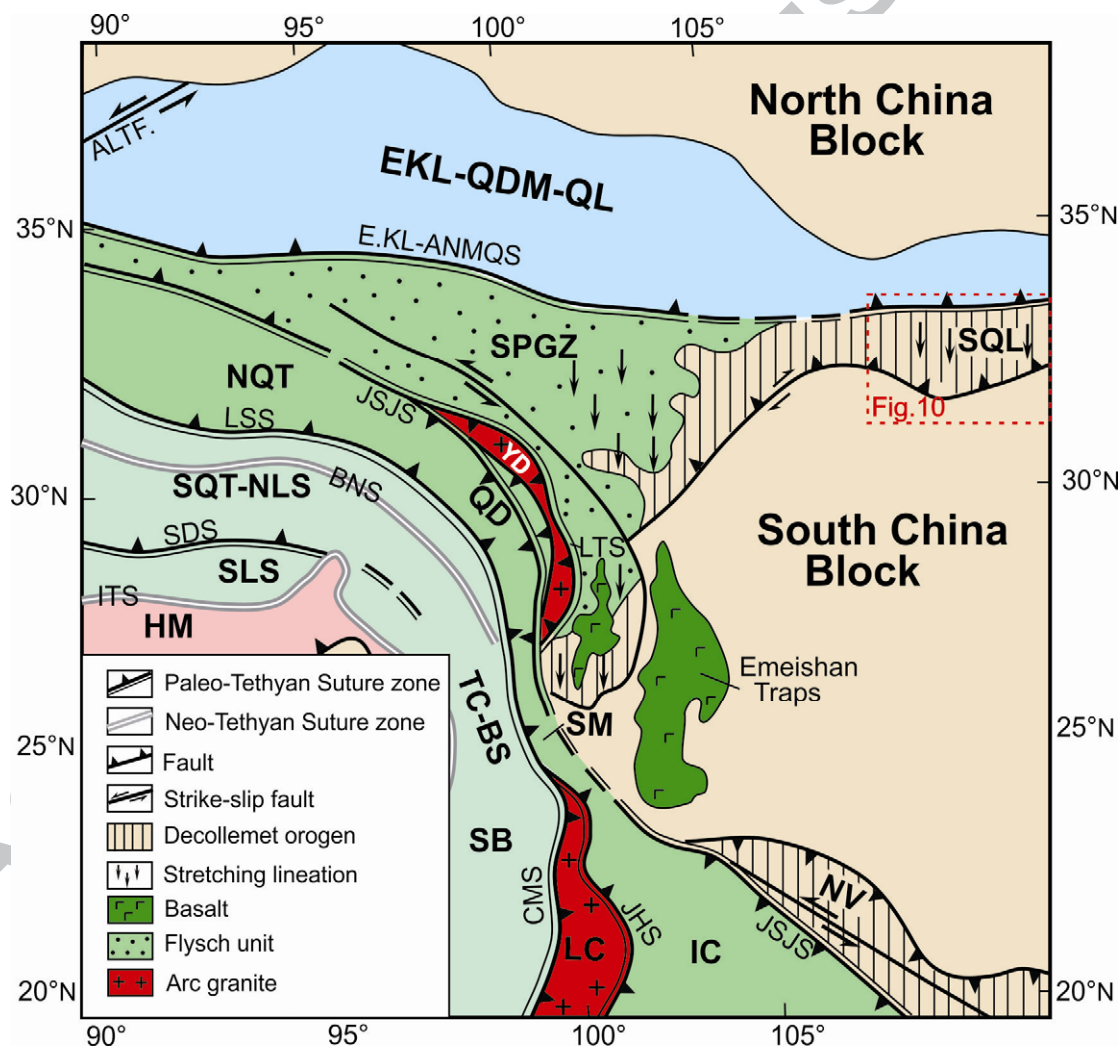
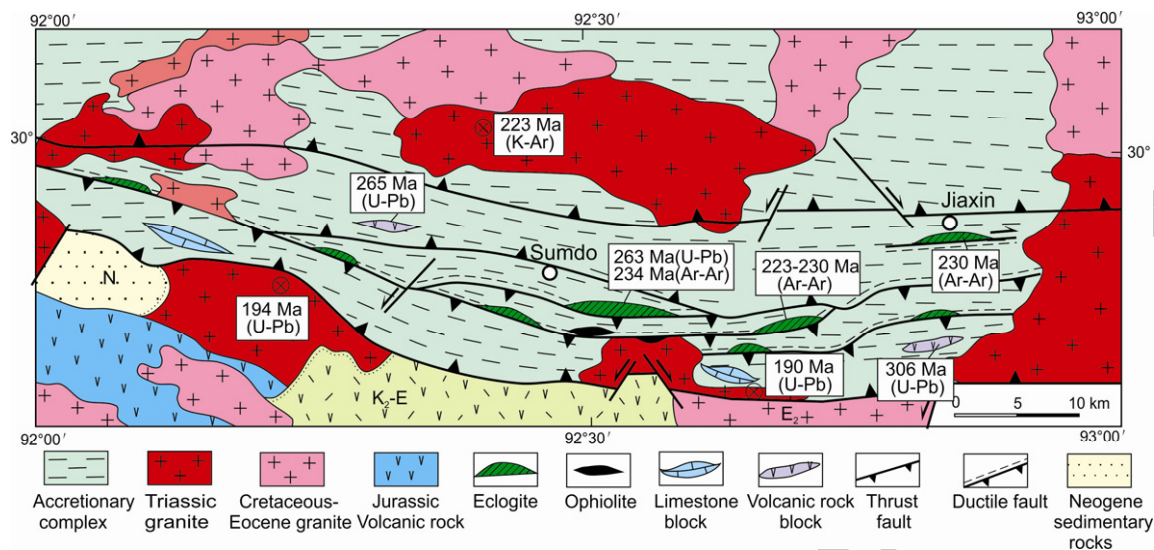
QT-Qiangtang; EKL-East Kunlun; SCB-South China block; DBD-Danba detachment.

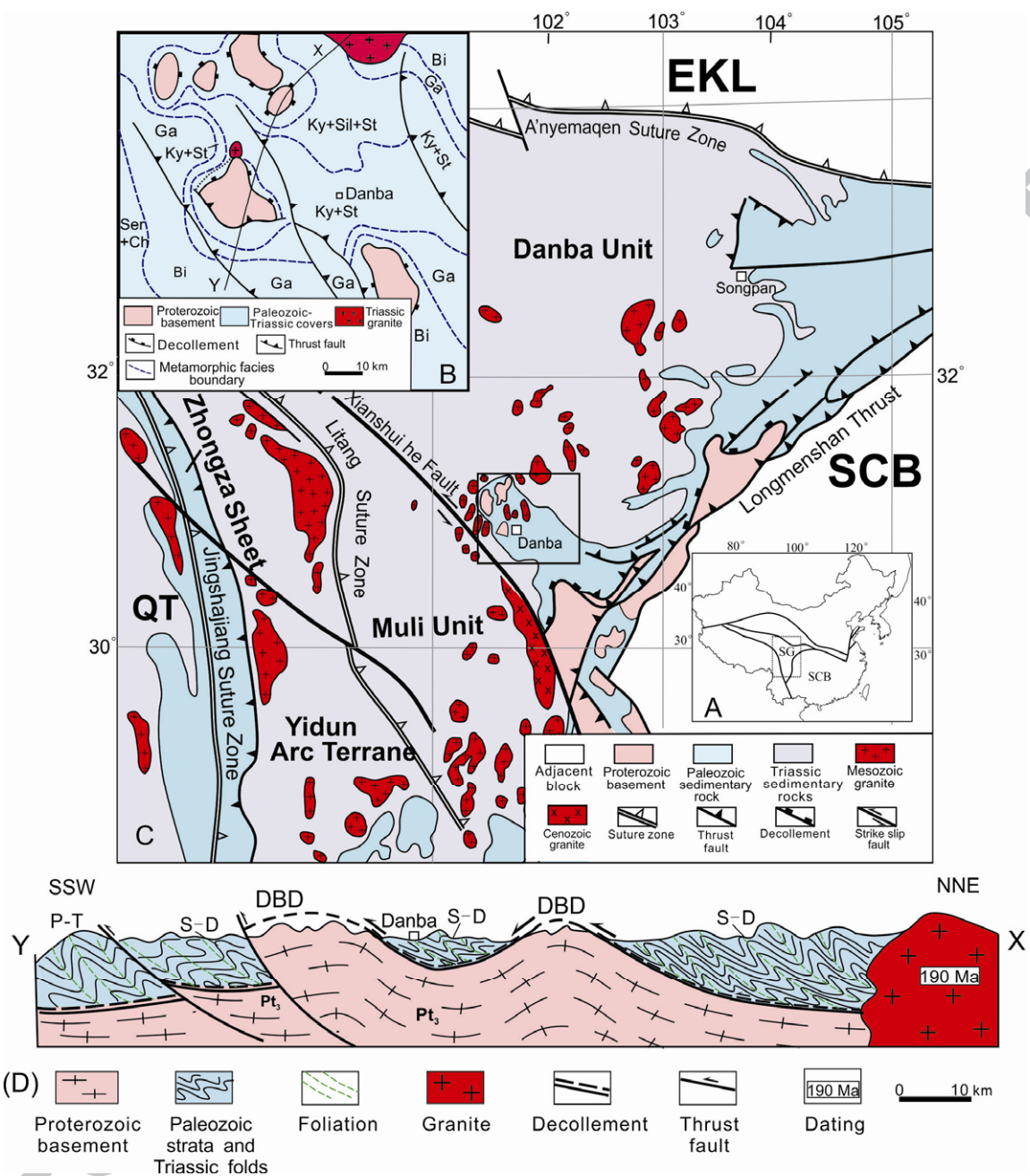
Figure 10. Schematic Tectonic Map (A), and cross-section (B) of the South Qinling orogen in the Northern South China block. Key to lettering: DFF-Dangfen Fault; FFX-Fangxian Fault; SYF-Shanyang Fault.

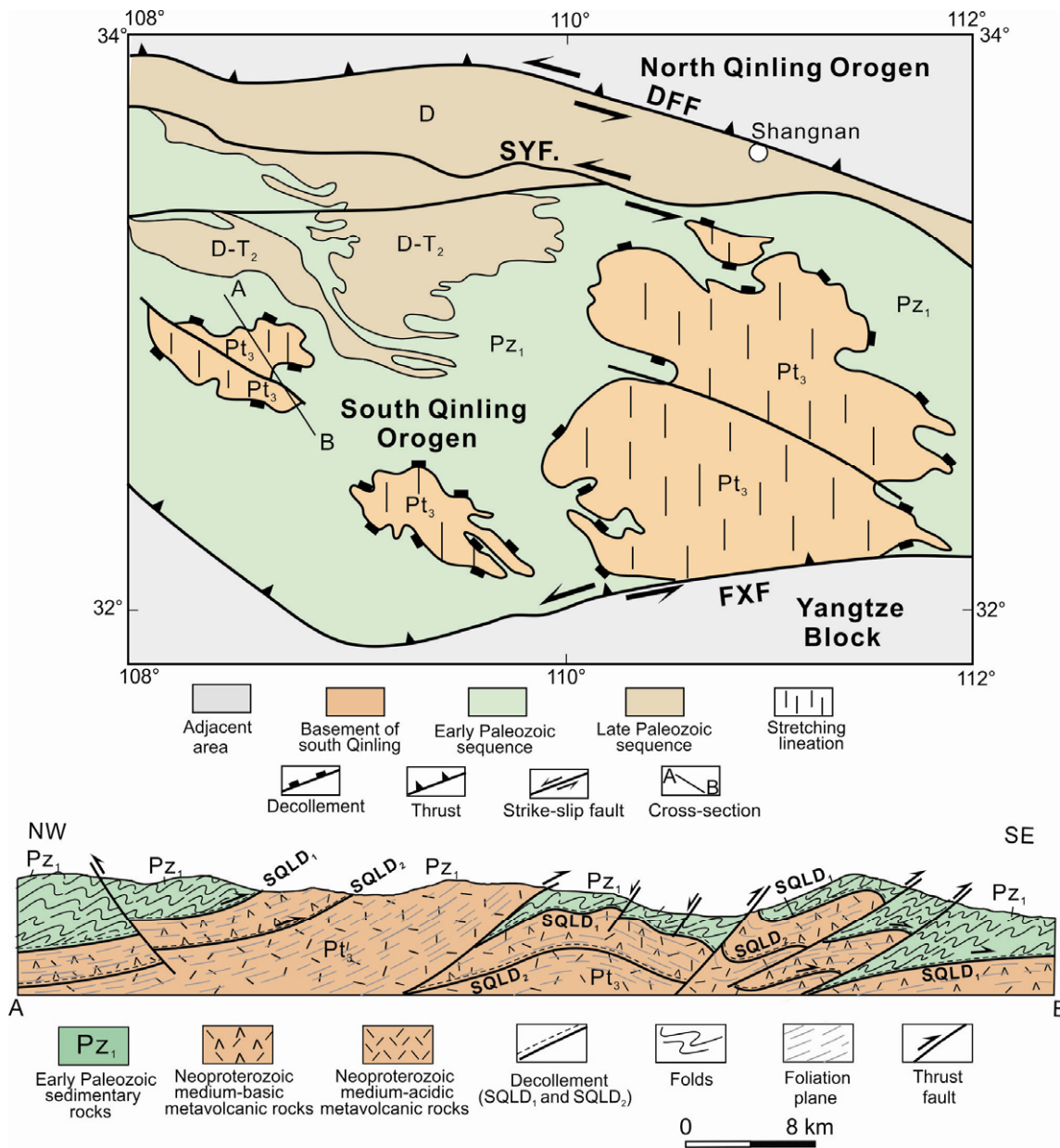
Figure 11. Sequential tectonic model for the evolution of the Paleo-Tethyan realm in Tibet. Key to lettering: LS-Lhasa; SD-Sumdo; JSJ-Jinshajiang; ANMQ-A'nyemaqen; BN-Bangong Nujiang Suture Zone; SLS-South Lhasa; NLS-North Lhasa; SQT-South Qiangtang; NQT-North Qiangtang; SP-Songpan; EKL-East Kunlun; CC-Continental Crust; LM-lithospheric Mantle.

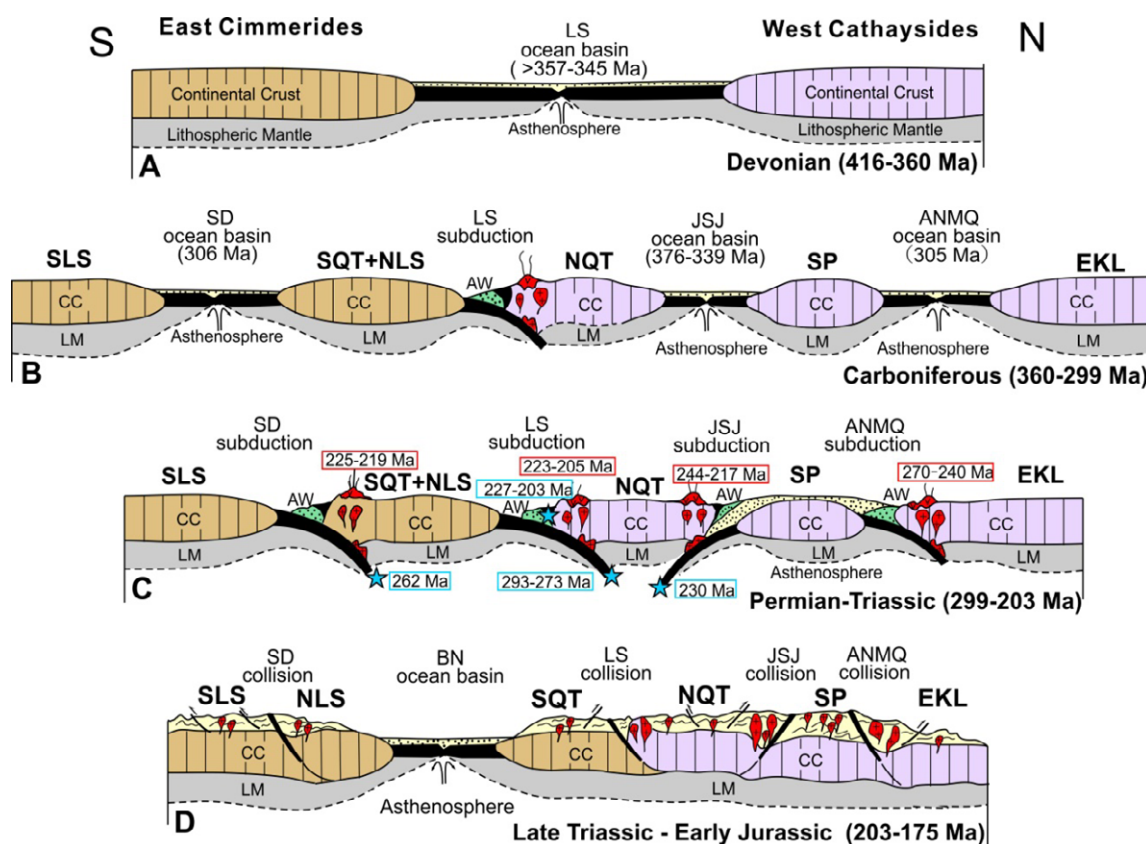












Highlights:

1. Paleo-Tethys system in Tibet consists of multi-terrane in East Cimmerides and West Cathaysides;
2. Longmucuo Shuanghu-Changning Menglian suture zone was the main suture zone;
3. Jinshajiang-Ailaoshan oceanic subduction shows a “trench-ridge- trench” triple junction model;
4. Decollement-type orogens occurred at western passive margin of South China Block

Paleo-Tethyan Evolution of Tibet as Recorded in the East Cimmerides and West Cathaysides

Zhiqin Xu^{a,b*}, Yildirim Dilek^{a, c}, Hui Cao^a, Jingsui Yang^a, Paul Robinson^d, Changqian Ma^e, Huaqi Li^a, Marc Jolivet^f, Françoise Roger^g, Xijie Chen^a

^aState Key Laboratory of Continental Tectonics and Dynamics, Institute of Geology, Chinese Academy of Geological Sciences, Beijing 100037, China

^bState Key Laboratory for Mineral Deposits Research, Department of Earth Sciences, Nanjing University, Nanjing 210093, China

^cDepartment of Geology & Environmental Earth Science, Miami University, Oxford, OH 45056, USA

^dDepartment of Earth Sciences, Dalhousie University, Halifax, Nova Scotia, Canada B3H4J1

^eChina University of Geosciences, Wuhan 430074, China

^fUMR 6118 - CNRS - University Rennes 1, Campus de Beaulieu, 35042 RENNES Cédex, France

^gUniversité Montpellier 2, Place Eugène Bataillon, 34095 Montpellier Cedex 05, France

Corresponding Author:

Dr. Zhiqin Xu

Tel.: +86-01068999663

Email: xuzhiqin@gmail.com

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